STANFORD UNIVERSITY
LOCKHEED MARTIN

The Gravity Probe B Detective Story

Presentation to

Dr. Turki Al-Saud

Vice President for Research Institutes

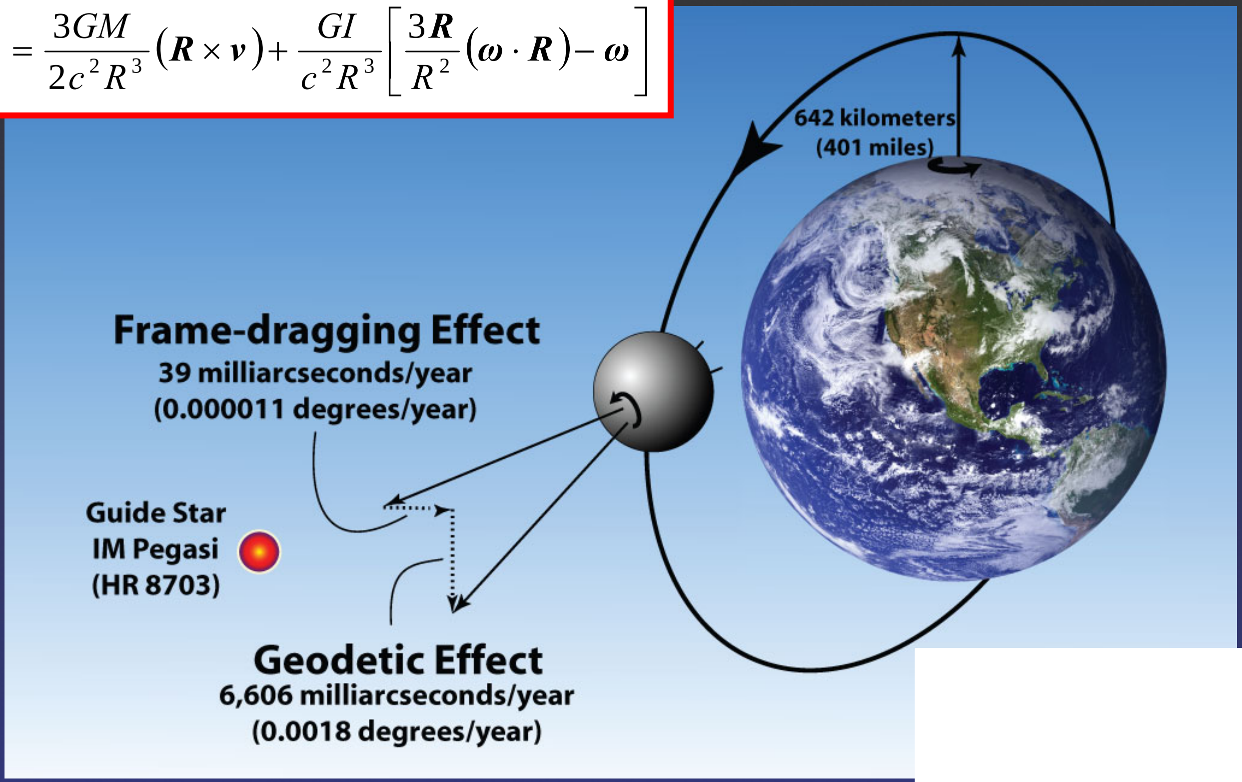
KACST

May 26, 2009

Francis Everitt

Orbiting Gyroscopes & Einstein

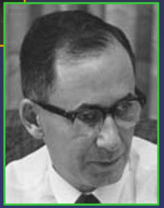
$$\boldsymbol{\Omega} = \frac{3GM}{2c^2R^3}(\boldsymbol{R}\times\boldsymbol{v}) + \frac{GI}{c^2R^3}\left[\frac{3\boldsymbol{R}}{R^2}(\boldsymbol{\omega}\cdot\boldsymbol{R}) - \boldsymbol{\omega}\right]$$

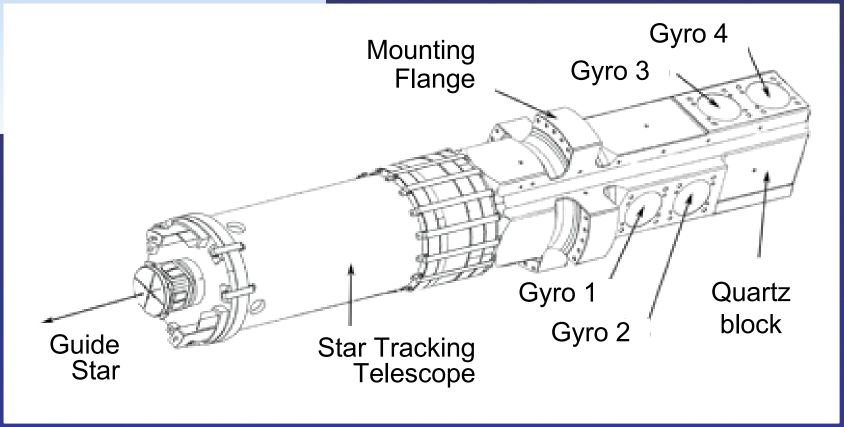


Mach

Thirring

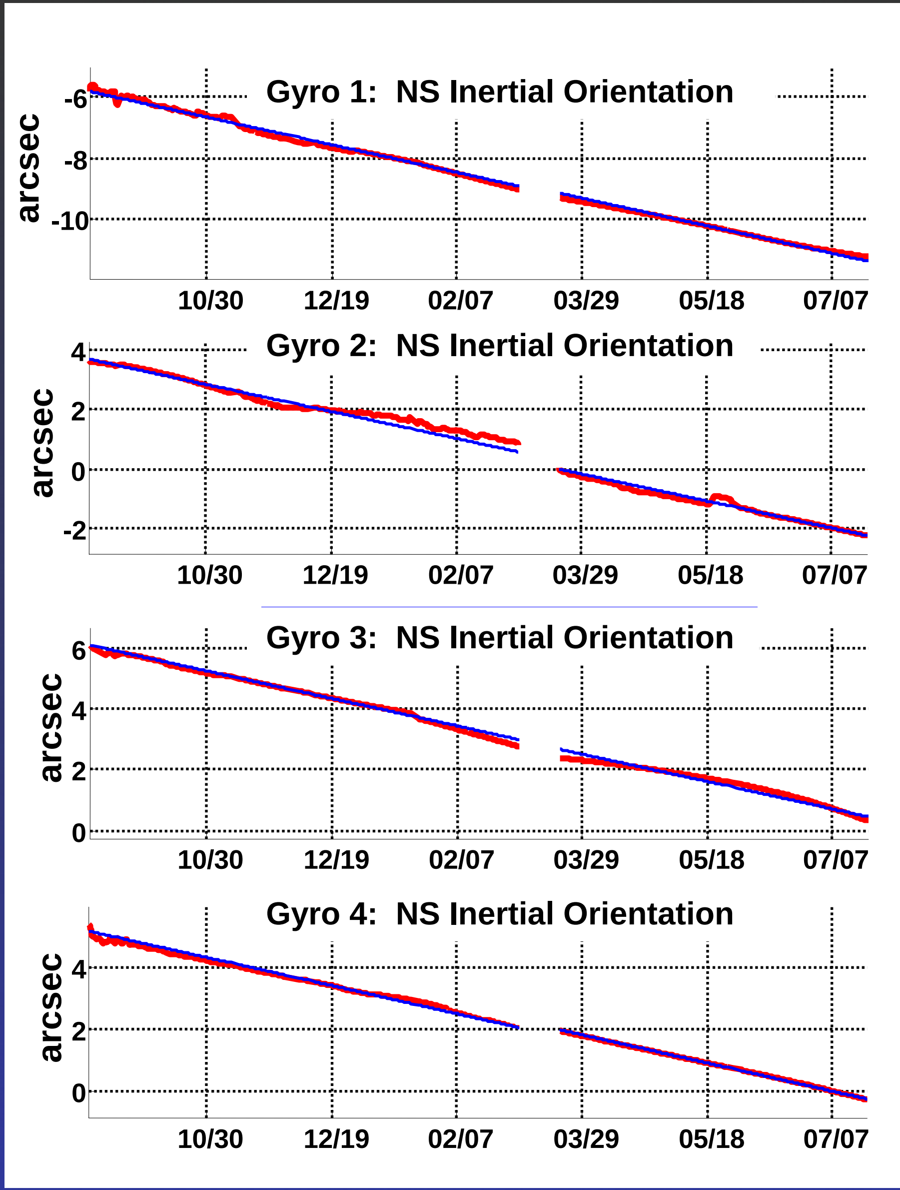
Schiff





- Geodetic Effect
  - Space-time curvature ("the missing inch")
- Frame-dragging Effect
  - Rotating matter drags space-time ("space-time as a viscous fluid")

Seeing GR in 'Raw' Data



Geodetic effect	marc-s/yr
Einstein expectation	- 6571 ± 1*
4-gyro result (1σ)	- 6578 ± 97

≤ 97 marc-s/yr estimate based on gyro-to-gyro disagreements & other systematics

SQUID noise limit (4-gyro)

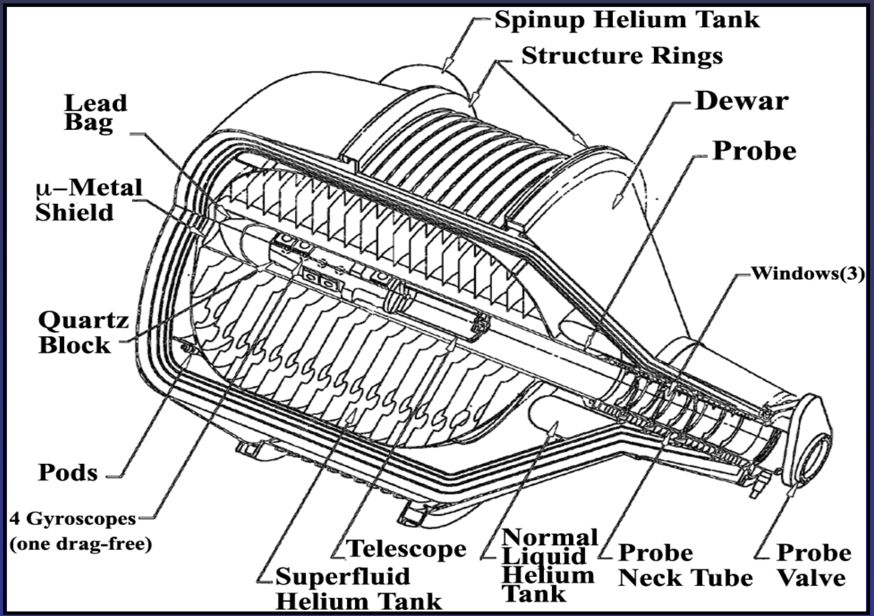
- 353 day continuous ± 0.12
- segmented data ± 0.5 - 0.9

* -6606 + 7 solar geodetic + 28 ± 1 guide star proper motion

0.1 marc-sec/yr = 3.2×10^{-12} deg/hr – width of a human hair seen from 100 miles

The 4 +1 GP-B Challenges

- Gyroscope (G) — 10^7 times better than best 'modeled' inertial navigation gyros
- Telescope (T) — 10^3 times better than best prior star trackers
- G – T → <1 marc-s subtraction within pointing range
- Gyro Readout → calibrated to parts in 10^5



Basis for 10^7 advance in gyro performance

Space

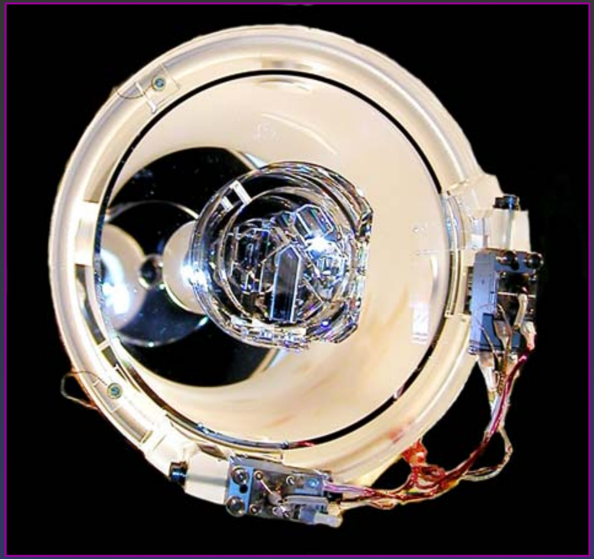
- reduced support force, "drag-free"
- roll about line of sight to star

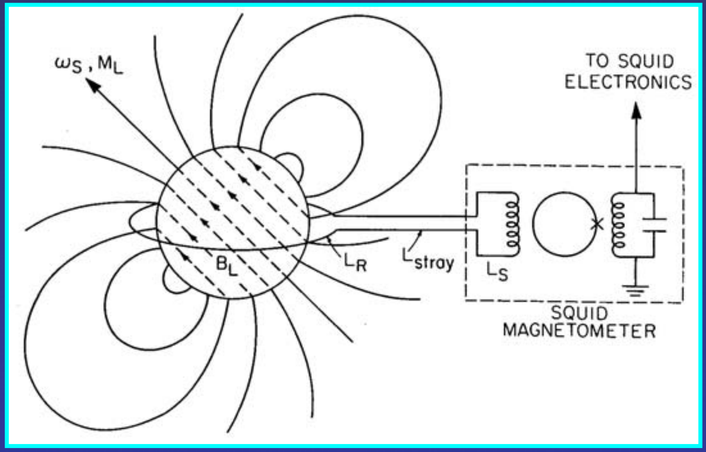
Cryogenics

- magnetic readout & shielding
- thermal & mechanical stability
- ultra-high vacuum technology

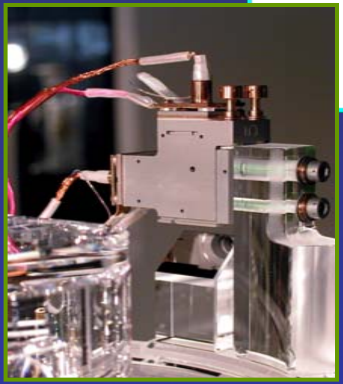
5th Challenge → Modeling *ad hoc vs physics-based*

Challenges 1 & 2: Gyro & Telescope





Detector Package



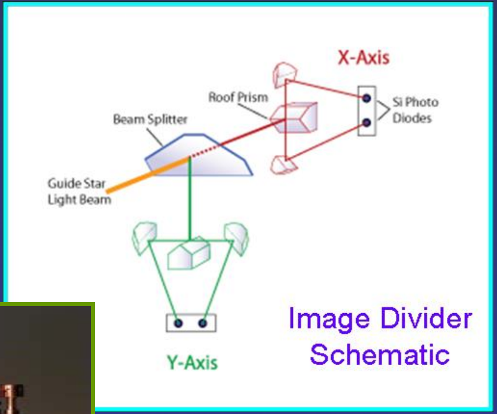
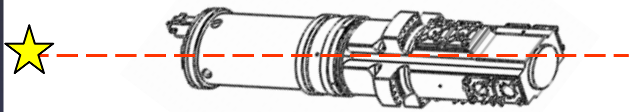


Image Divider Schematic

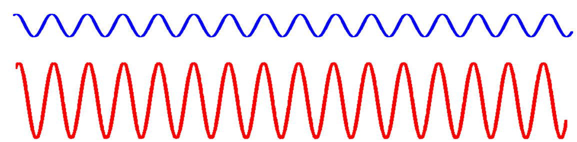
Si Diode Detector

Challenges 3 & 4: Matching & Calibration

Dither -- *Slow 60 marc-s oscillations injected into pointing system*

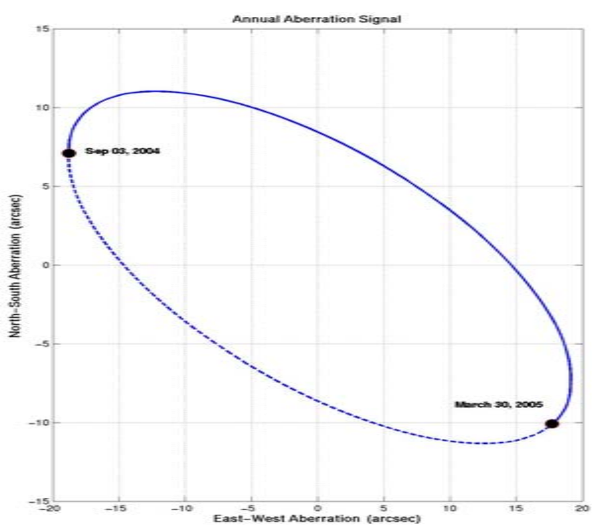


gyro output
telescope output



scale factors matched for accurate subtraction

Aberration -- *Nature's calibrating signal for gyro scale factor* C_g



Orbital motion ⇒ varying apparent position of star
(v_{orbit}/c + special relativity correction)

Earth around Sun -- 20.4958 arc-s @ 1-year period
S/V around Earth -- 5.1856 arc-s @ 97.5-min period

⇒ Continuous accurate calibration of GP-B experiment

Actualities of GP-B

Good

- **gyroscopes**
  - *10^6 times better than best inertial navigation gyroscopes*
  - *SQUID noise < expected*
  - *excellent charge control & centering stability*
  - *τ's ~ 7200 to 26,100 years*
- **telescope**
  - *superb overall performance*
- **dewar**
  - *beats design hold time*
- **orbit within 100 m of ideal**

Less than ideal

- *polhode rate variation*
- *misalignment torque*
- *resonance torque*

- *segmented data*
- *interference from ECU*
- *out-of-spec pointing*

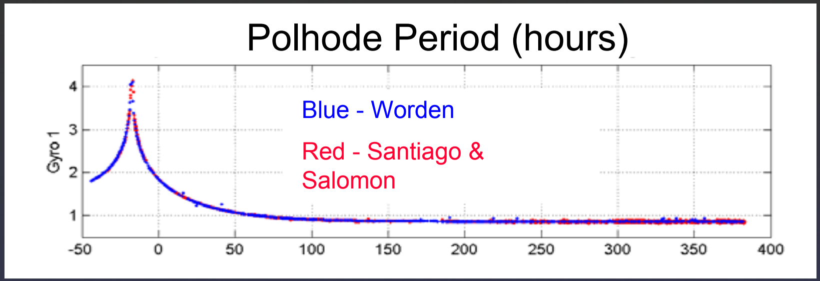
5th Challenge

Gremlins, data grading & systematics

3 Gremlins

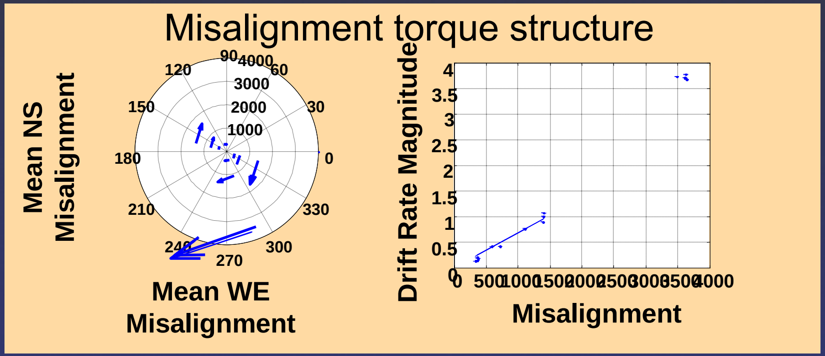
A. Polhode-rate variations

- A big surprise in early science phase
- Complicates C_g determination



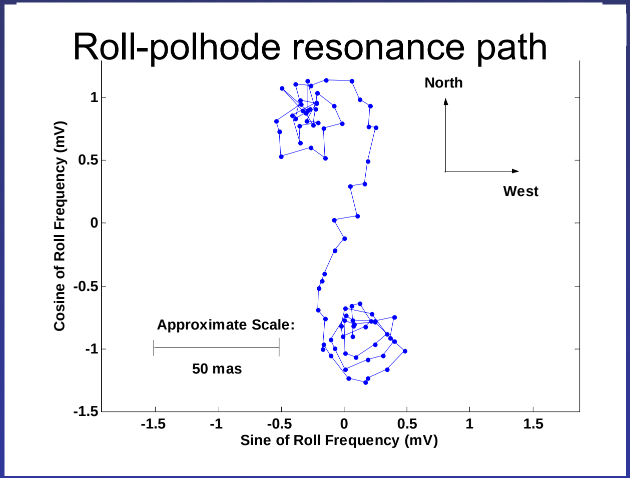
B. Misalignment torques

- Pointing to other stars gives much-bigger-than-expected gyro drifts



C. Resonance torques

- Gyro-to-gyro comparisons reveal periodic jumps in individual gyro orientations



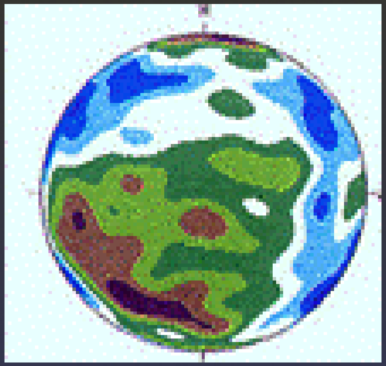
All due to one cause (patch effect)

Roundness & Out-of-Roundness

1 Mechanical – *Good & Essential*

Rotor ~ 5 x 10^{-7} Housing ~ 4 x 10^{-6}

Gyro Contours



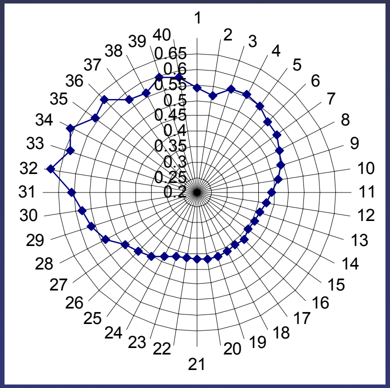
2 Electrical – *Bad & Very Unexpected*

Large sideways forces from 'patch effect' voltages

rotor surface

housing surface

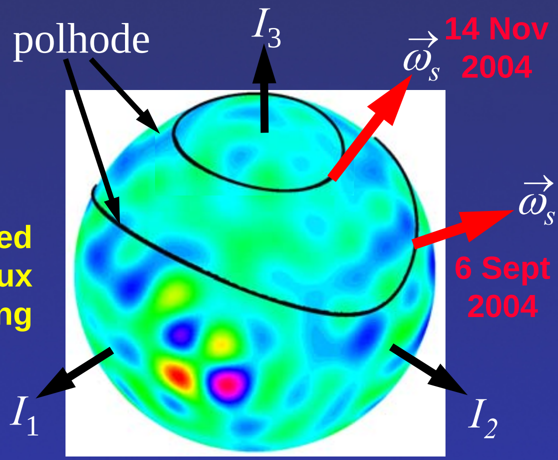
Work function polar plot



3 Magnetic – *Seemingly Bad, Miraculously Good!*

Rotor ~ 0.4% - 5% of London Moment

Trapped Flux Mapping



3 Breakthroughs

1. Aug 2006: 'Geometric' Method [Gremlin B]

2. Aug 2007: Trapped Flux Mapping [Gremlins A & C]

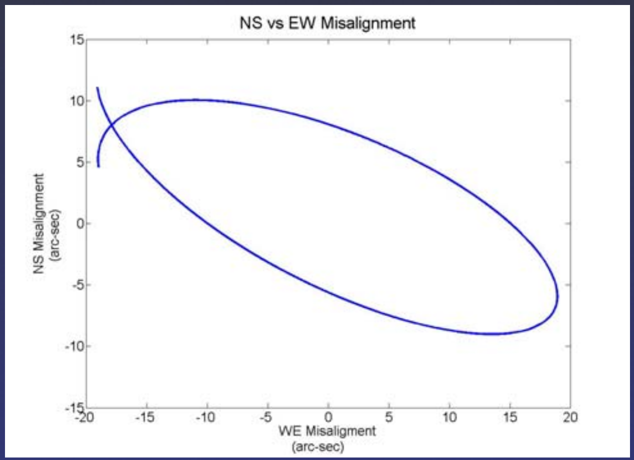
3. Aug 2008: Full Torque Modeling [Gremlins B & C]

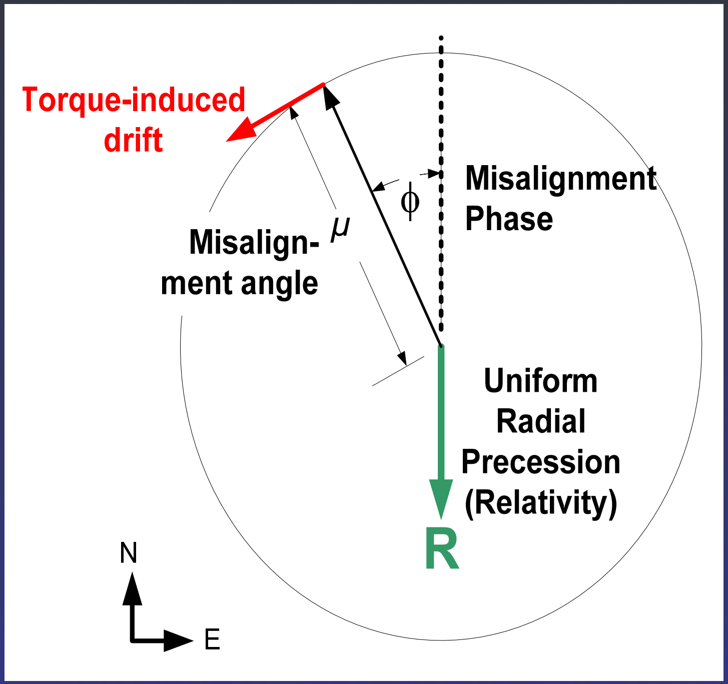
Breakthrough 1 [Aug '06]

A Geometrical Insight

- Annual aberration alters misalignment torque direction
- A truly *physical* modeling process

Mac Keiser





The 2 Methods

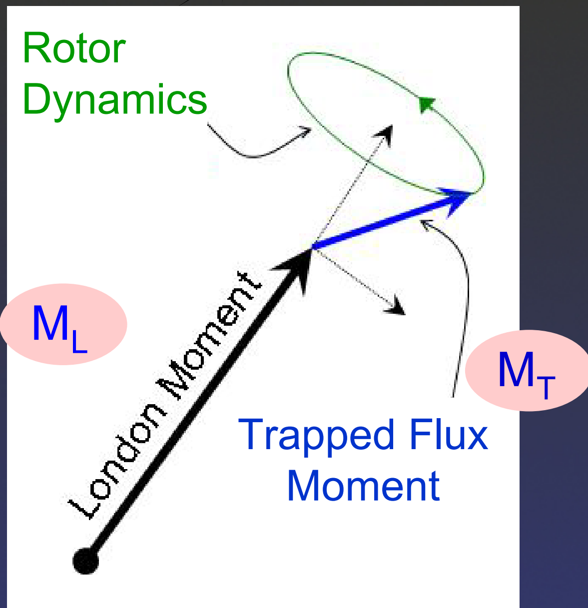
Geometric: Change variables to plot rates against misalignment phase

→ component of relativity free of misalignment torques

Algebraic: Filtering machinery to explicitly model torques

→ provides separation from relativity

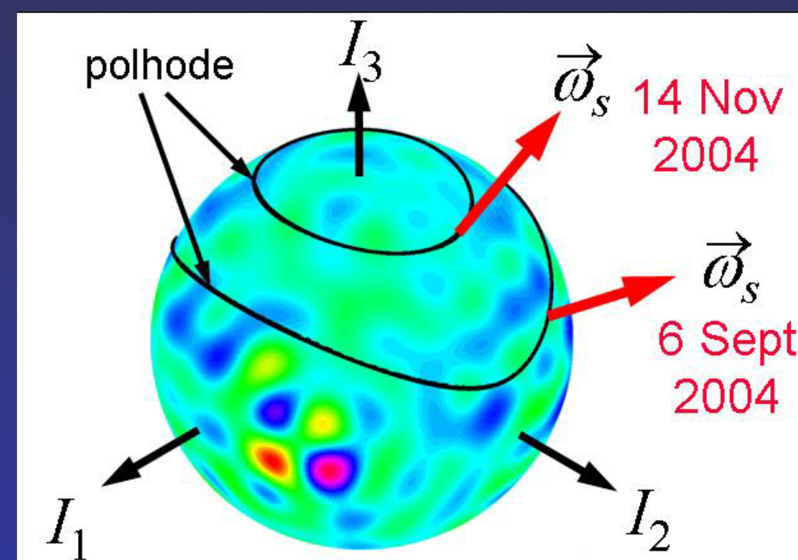
Ideal vs. Actual M_L Readout



London field at 80 Hz: 57.2 μG

Trapped fields
- Gyro 1 3.0 μG
- Gyro 2 1.3 μG
- Gyro 3 0.8 μG
- Gyro 4 0.2 μG

Detailed Trapped Flux Mapping (TFM)



3 Key Students

John Conklin

Michael Dolphin

Michael Salomon

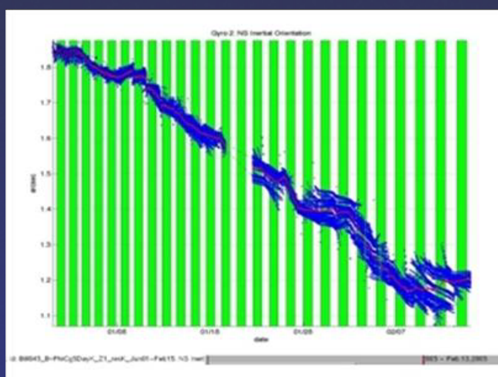
Breakthrough 2 [Aug ’07]

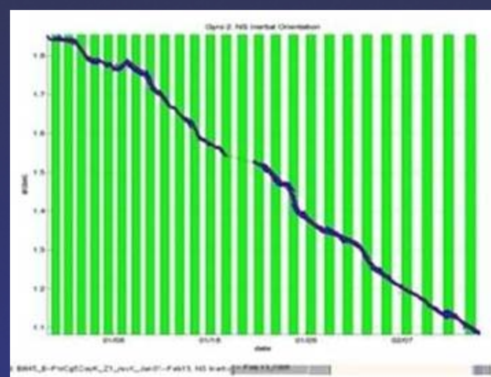
Accurate C_g Determination

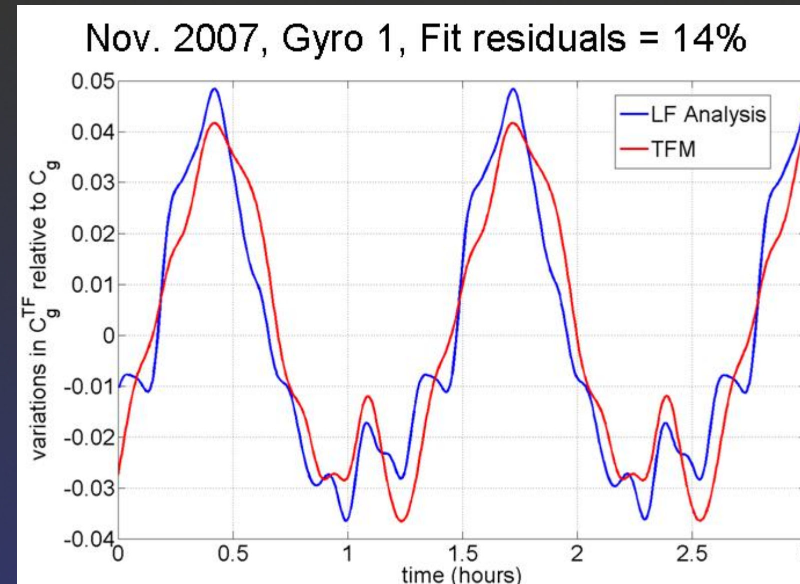
– Prior to Aug ’07
  - ➢ batch processing, large scatter

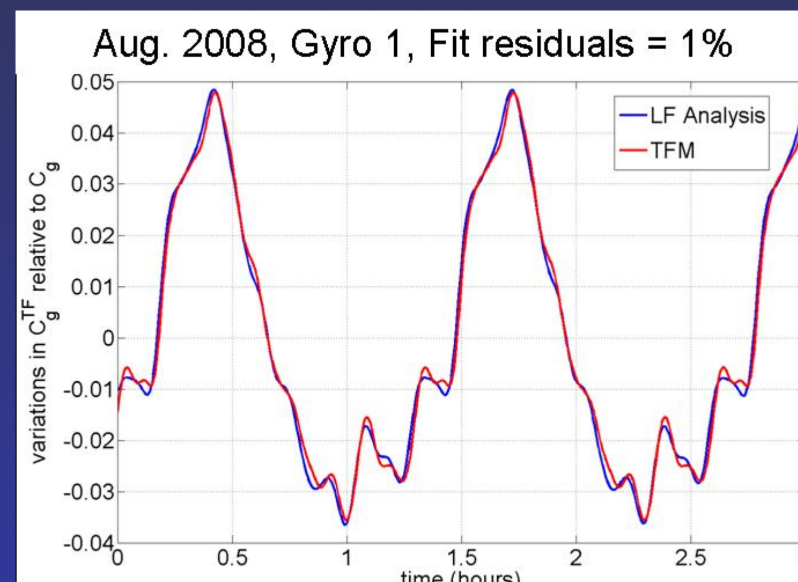
– Initial TFM treatment
  - ➢ → 100σ to 6σ to 2σ

Tom Holmes







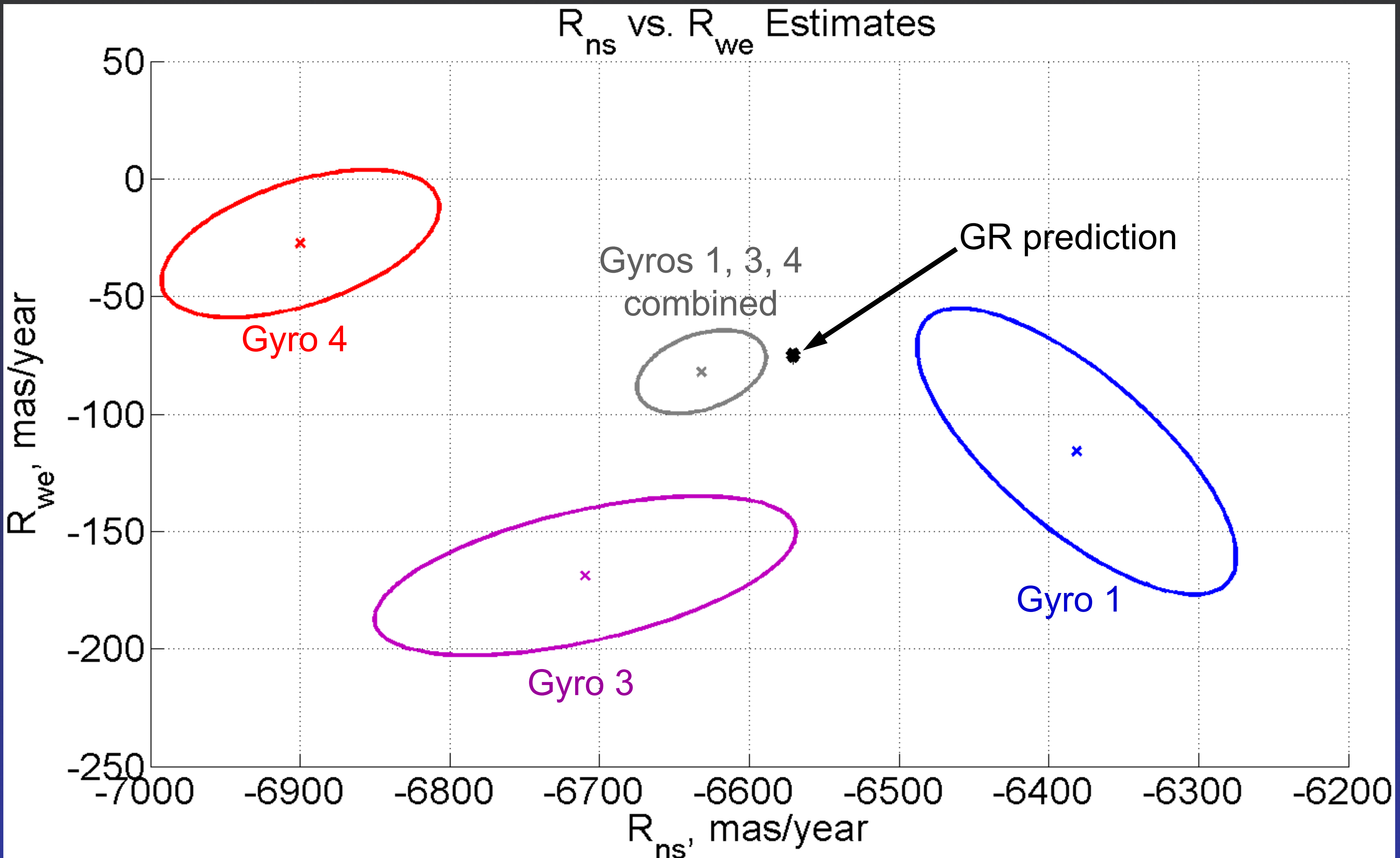


TFM determines evolving polhode phase to 1° over the full mission

→ Resolves scale factor issue

→ Critical input for torque analysis

After Breakthroughs 1 & 2 [Nov '07]



Breakthrough 3 [Aug 2008]

- Add resonance torque model to equations of motion

$$\frac{ds_{NS}}{dt} = r_{NS} + k(t)\mu_{EW} + \sum A_m(t)\cos\Delta\phi_m - B_m(t)\sin\Delta\phi_m$$
$$\frac{ds_{EW}}{dt} = r_{EW} - k(t)\mu_{NS} + \sum A_m(t)\sin\Delta\phi_m + B_m(t)\cos\Delta\phi_m$$

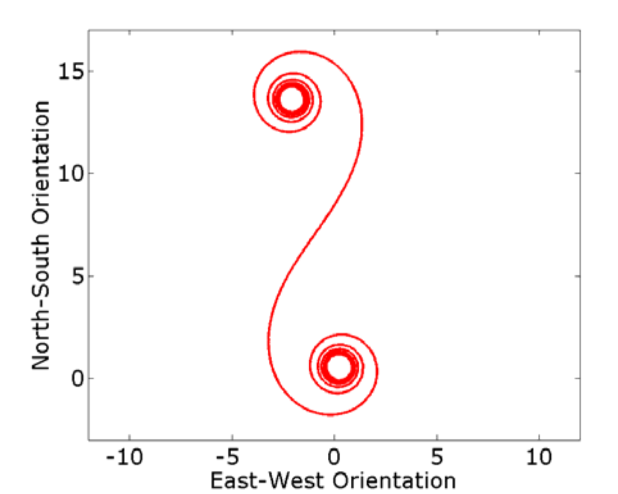
Relativity   Misalignment torque   Resonance torque

- Resonance condition $\longrightarrow$ $\Delta\phi_m = \phi_{\mathrm{roll}} - m\phi_p$

$\longrightarrow$ Treatment of roll-polhode term hinges on TFM

Resonance Torque Dynamics

- Path predicted from rotor & housing potentials
  - Roll averaging fails when $\omega_r = n\omega_p$
  - Orientations follow Cornu spiral
  - Magnitude & direction depend on patch distribution, roll & polhode phases at resonance



- Example: Gyro 2, Resonance 277 – Oct 25, '04

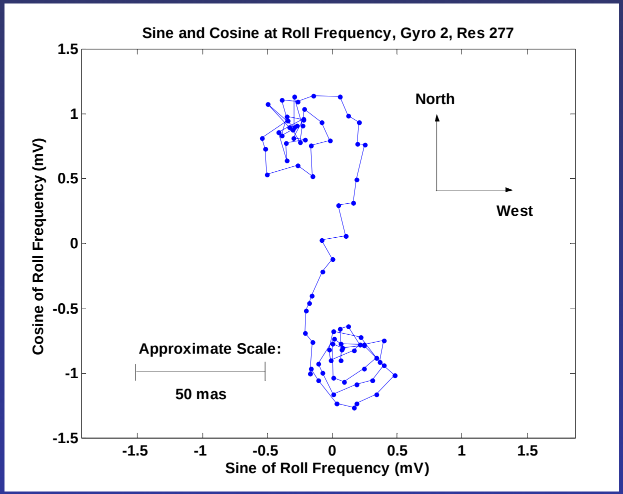

Jeff Kolodziejczak


Mac Keiser

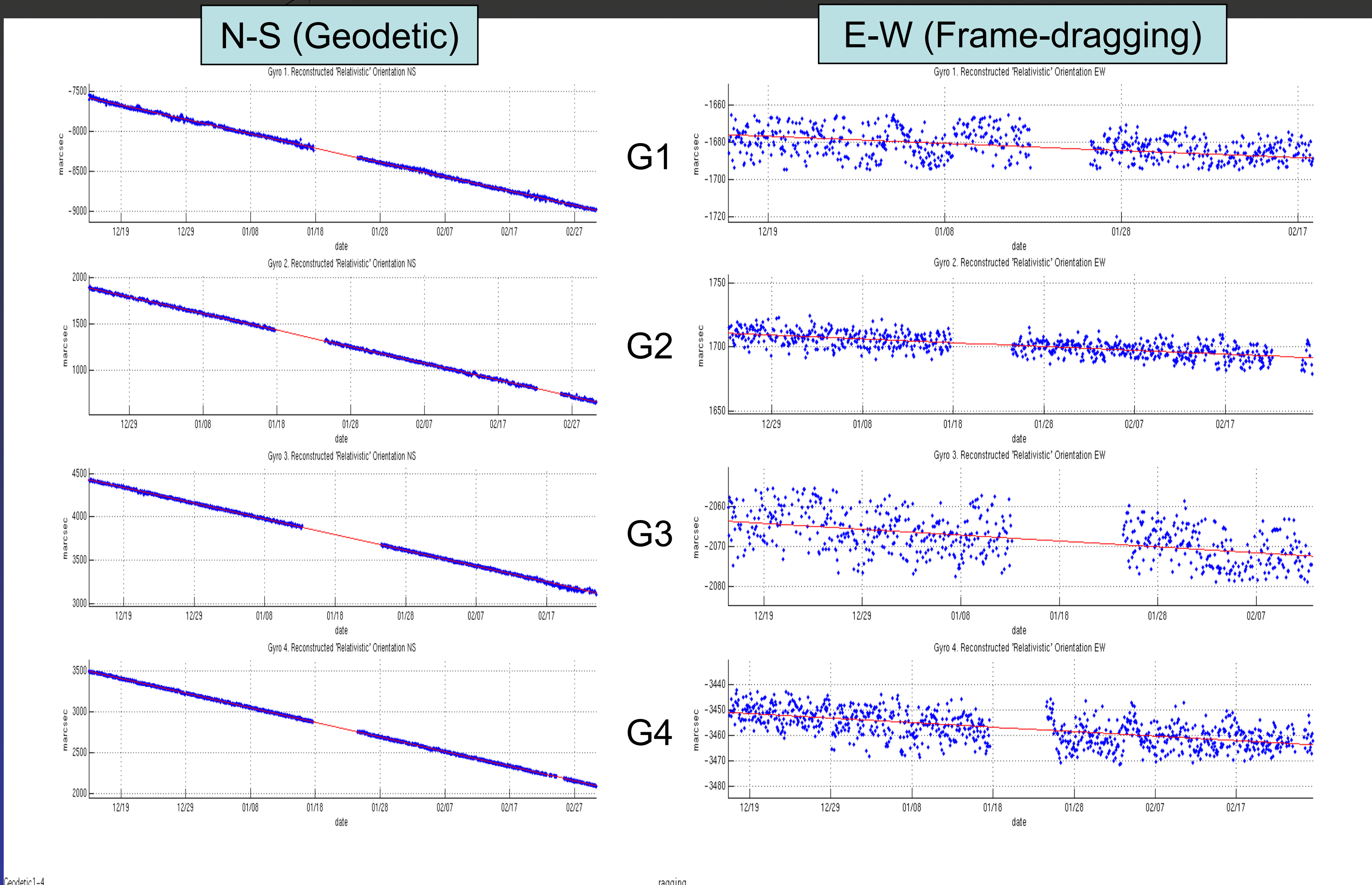

Alex Silbergleit


Michael Heifetz

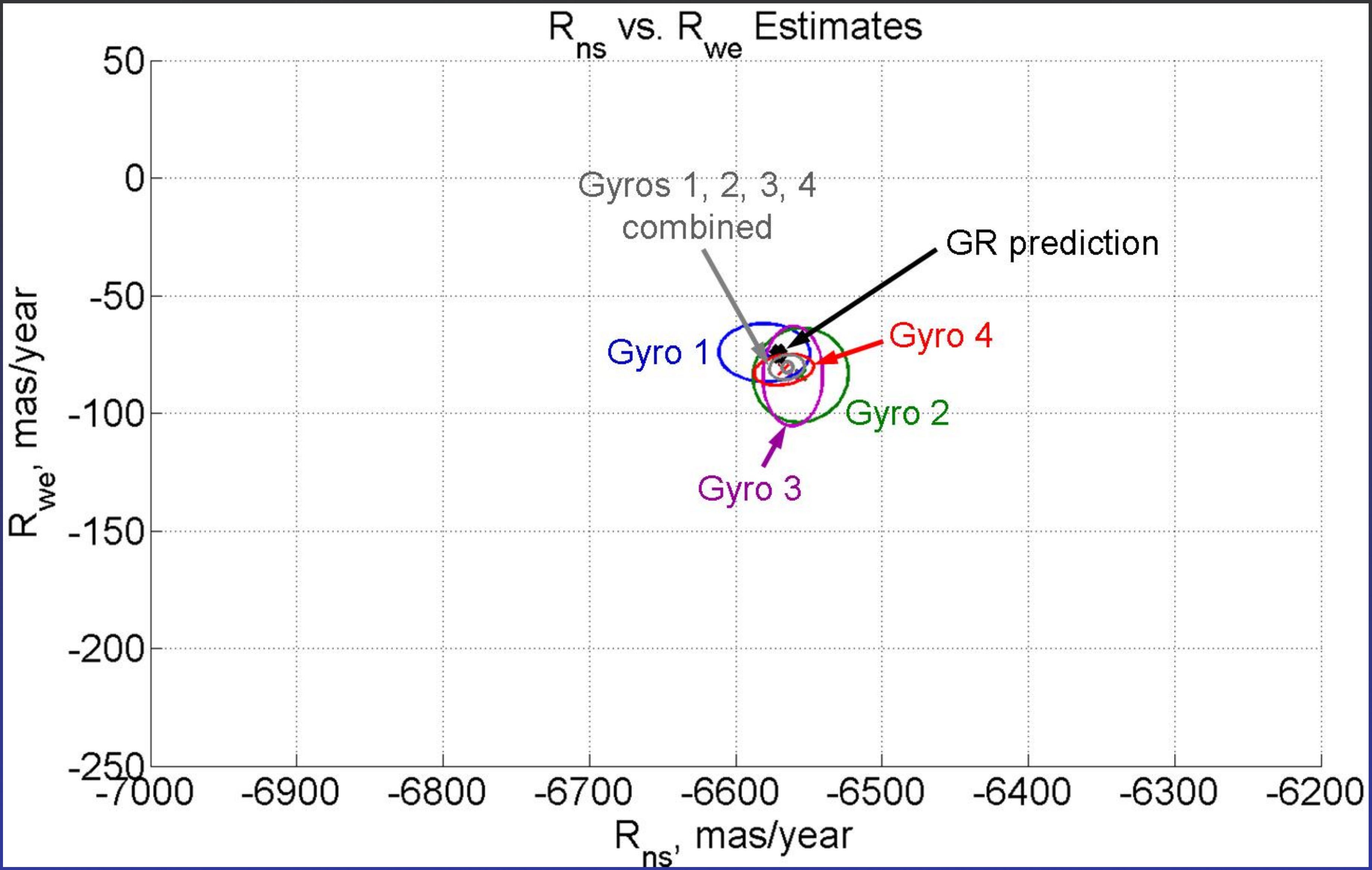

Vladimir Solomonik



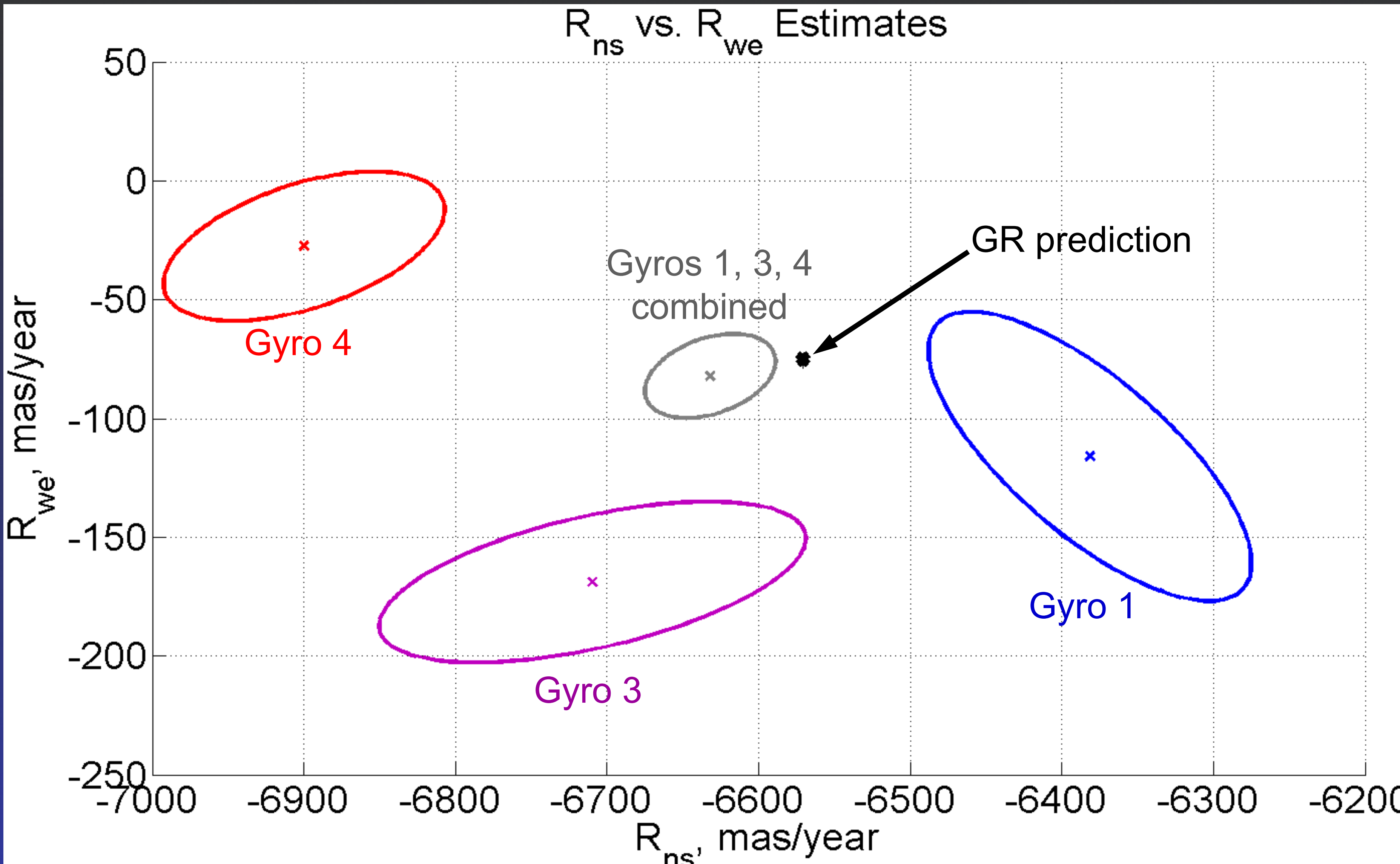
Full Model Results as of Dec '08 - I



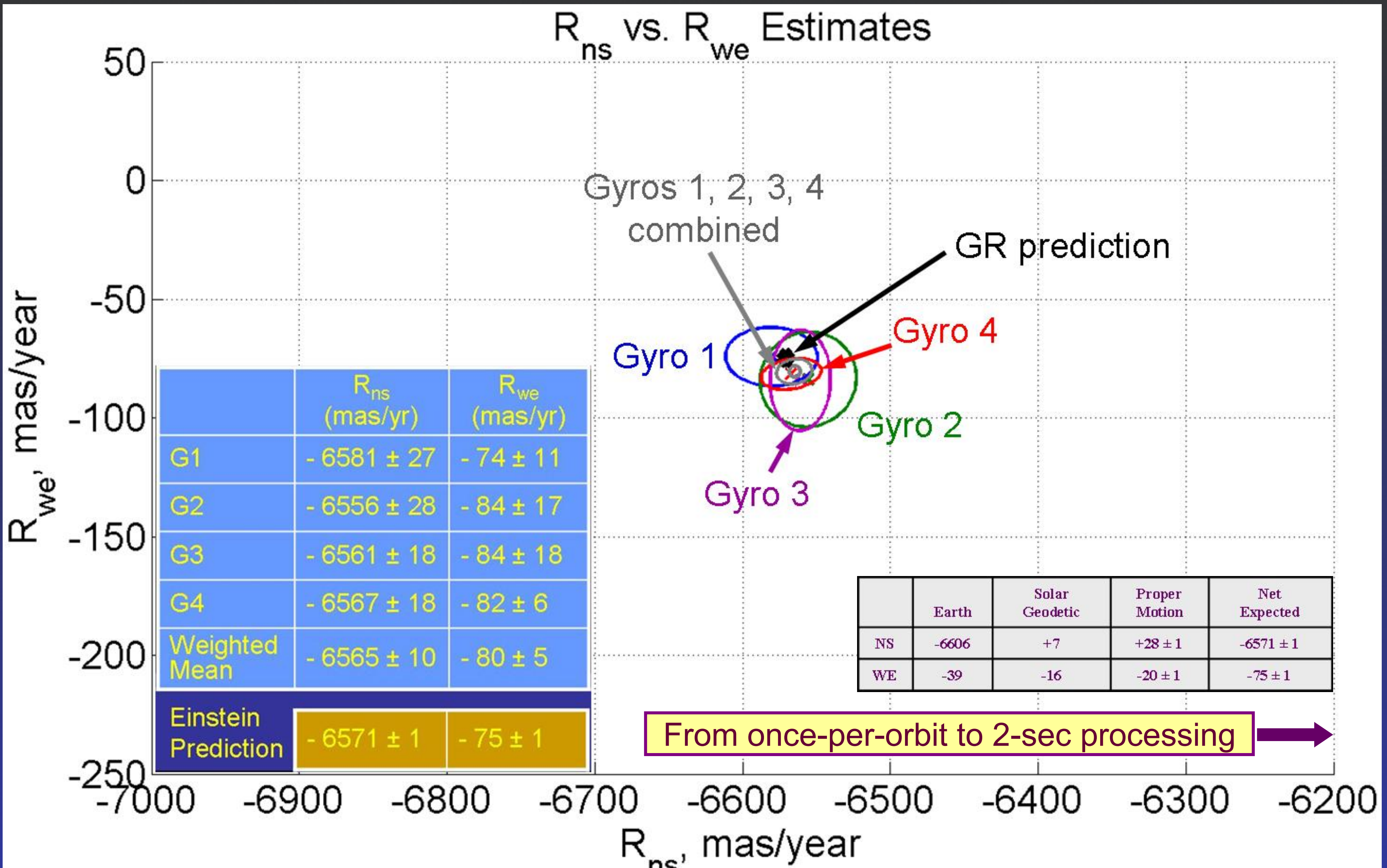
Full Model Results as of Dec '08 - II



After Breakthroughs 1 & 2 [Nov '07]



Full Model Results as of Dec '08 - II



	R_{ns} (mas/yr)	R_{we} (mas/yr)
G1	- 6581 ± 27	- 74 ± 11
G2	- 6556 ± 28	- 84 ± 17
G3	- 6561 ± 18	- 84 ± 18
G4	- 6567 ± 18	- 82 ± 6
Weighted Mean	- 6565 ± 10	- 80 ± 5
Einstein Prediction	- 6571 ± 1	- 75 ± 1

	Earth	Solar Geodetic	Proper Motion	Net Expected
NS	-6606	+7	+28 ± 1	-6571 ± 1
WE	-39	-16	-20 ± 1	-75 ± 1

From once-per-orbit to 2-sec processing

Independent Geometric Results

1 R_{NS} & R_{WE}

Best so far for Gyro #4

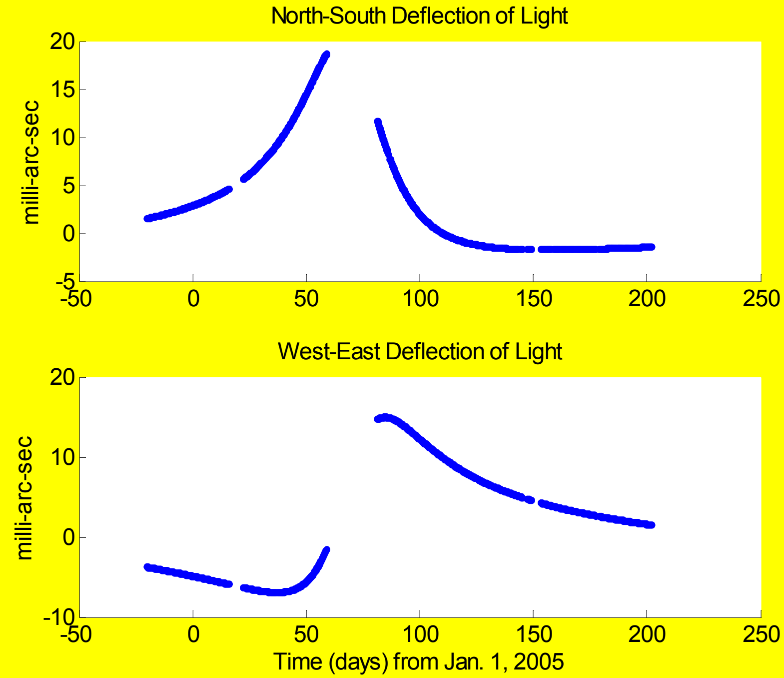
$$R_{NS} = -6631 \pm 16 \; mas/yr$$
$$R_{WE} = -77 \pm 14 \; mas/yr$$

2 Gravitational deflection of light

Nearest approach to Sun

Date: March 11

Ecliptic Latitude: 22.1°



Result to date $\lambda = 1.20 \pm 0.17$

3 24.65-day guide star orbital motion

$$a_{NS} = -1.65 \pm 0.14 \; mas \qquad b_{NS} = -0.36 \pm 0.14 \; mas$$
$$a_{WE} = -0.11 \pm 0.12 \; mas \qquad b_{WE} = -0.61 \pm 0.13 \; mas$$

Are we done?

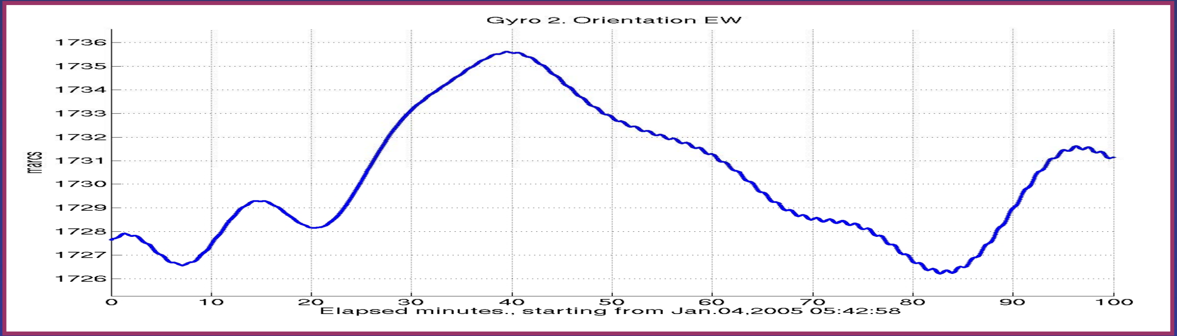
- **Current '2 floor' 4-gyro result ~ 5 marcs/yr**
  - limited by ⟶ { once-per-orbit time step; 3 out of 10 segments (158 days vs. 333 days) }

- **Fundamental & operational limits**
  - SQUID noise 0.14 – 0.35 marcs/yr (gyro dependent)
  - Covariance ~ 1 marcs/yr (4 gyros combined)

$$\frac{ds_{NS}}{dt} = r_{NS} + k(t)\mu_{EW} + \sum A_m(t)\cos\Delta\phi_m - B_m(t)\sin\Delta\phi_m$$

$$\frac{ds_{EW}}{dt} = r_{EW} - k(t)\mu_{NS} + \sum A_m(t)\sin\Delta\phi_m + B_m(t)\cos\Delta\phi_m$$

$$\Delta\phi_m = \phi_{\mathrm{roll}} - m\phi_p$$



Accurate integration requires time step << 1 orbit ⟶ *parallel processing*

Advanced (2-sec) Filter Development

Two simultaneous development activities

Co-PI Charbel Farhat

1. Serial processing → ***accuracy***
   - built on 4-years' experience with 2-floor (once per orbit) filter
   - accurately models the physical phenomena
   - has passed truth test – ***Badr Alsuwaidan***

2. Parallel processing → ***speed***
   - ~ 10x faster (3 day analysis → overnight)
   - requires computer cluster
   - ~ 10% modified/additional code – ***Majid Almeshari***

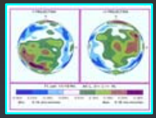
Path to Completion

- **Serial 2-sec processing (segments 5, 6, 9)** ***Aug ’09***
- **Complete transition to parallel processing** ***Oct ’09***
- **Extension from 5, 6, 9 to all segments** ***Dec ’09***
- **Complete treatment of systematics** ***Feb ’10***
- **Grand synthesis**
  ⇨ **approach ~ 1 marcs/yr 4-gyro limit** ***Jun ’10***

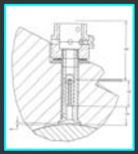
Final results to be announced at Fairbank Workshop on Fundamental Physics & Innovative Engineering in Space ***Aug ’10***

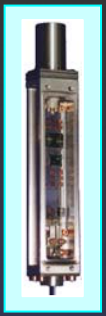
Heritage of GP-B for KACST-Stanford

- Technologies

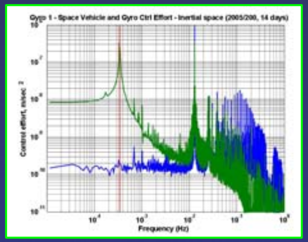


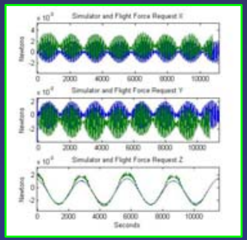



- Vehicle & active control center
  (B. Muhlfelder)


- Precision ATC
  (J. Mester)





- STEP
  (P. Worden, J. Mester)